Advanced Fuels for Fast Reactors
The U.S. Perspective

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U.S. Fast Reactor Fuel Development

- Early work on metals, oxides, nitrides and carbides (FFTF, EBR-II experiments)
- IFR Program until 1994 - Metallic Fuels
- ATW, AAA, Early AFCI - Metal, nitride
  - Oxides primarily through international collaborations
- GNEP/AFCI - Oxides and metals
  - Highest technology readiness levels (TRL)
- AFRD - Science based understanding in search of high performance fuels
  - Work on metals and oxides will continue

A consistent TRL binning against the fabrication and performance attributes is developed.

Performance Maturity

	Fundamental Property Measurements	Out-of-Pile Testing	In-Pile Testing Representative Spectrum	Transient Testing	In-Pile Testing Prototypic Spectrum	Reactor Operations
Multiple Assemblies (Core Loads)						TRL 8 - 9
Few Assemblies					TRL 7	TRL 8
Pins		TRL 4	TRL 5	TRL 5-6	TRL 6	
Samples & Rodlets	TRL 4	TRL 4	TRL 4	TRL 5	TRL 5	

Fabrication Maturity

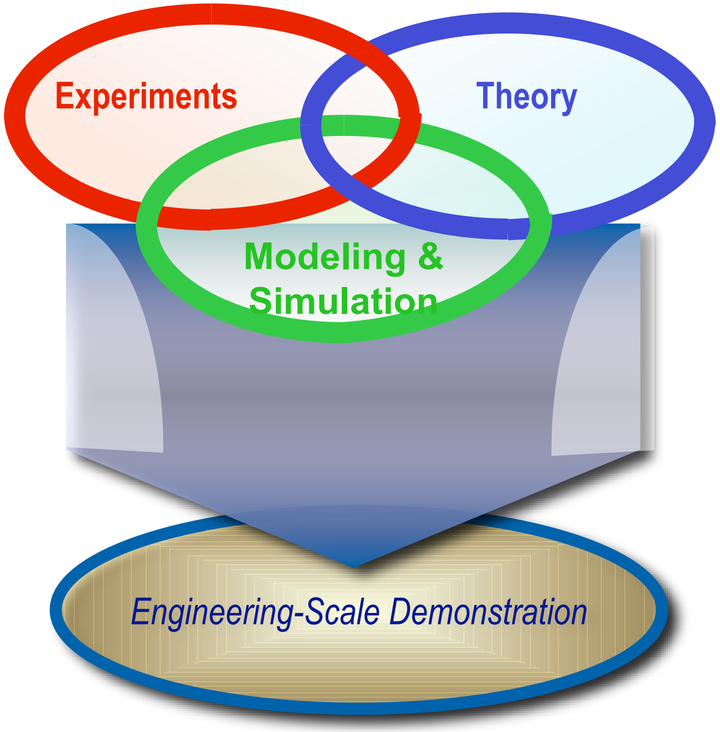
	Bench-Scale (1g - 1 kg)	Laboratory-Scale (1 - 10 kg)	Engineering-Scale (10 - 100 kg)	Commercial-Scale (> 1 ton)
Representative Materials from Separations Process	TRL 4 - 5	TRL 6	TRL 7	TRL 8 - 9
Representative Materials from Stockpile	TRL 4	TRL 4 - 5		
Surrogate Materials	TRL 3			

A balanced approach for TRL definition considering both the fabrication and performance aspects is needed.

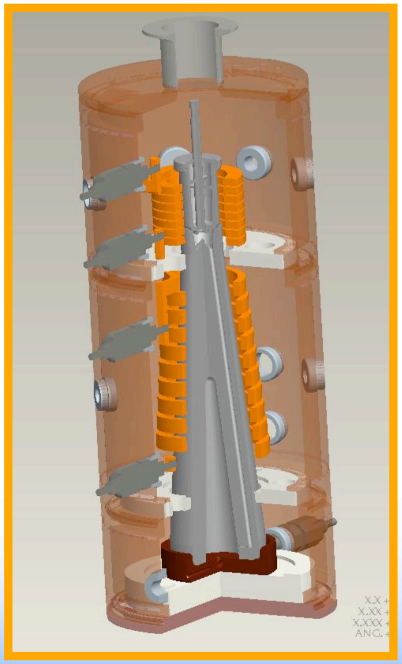
One aspect being way ahead of the other is not useful.

Metal fuel is an essential element of the current development program for TRU-Bearing FR Fuels

- Fabrication technology
  - U, Pu, Np, Am, Zr
- Characterization techniques
  - Emphasis on microstructural characterization and local properties measurement
- Irradiation
  - Thermal and fast reactor irradiations
  - Separate effect/Phenomenological tests
- Post-Irradiation Examination
- Cladding Development
- Modeling and Simulation



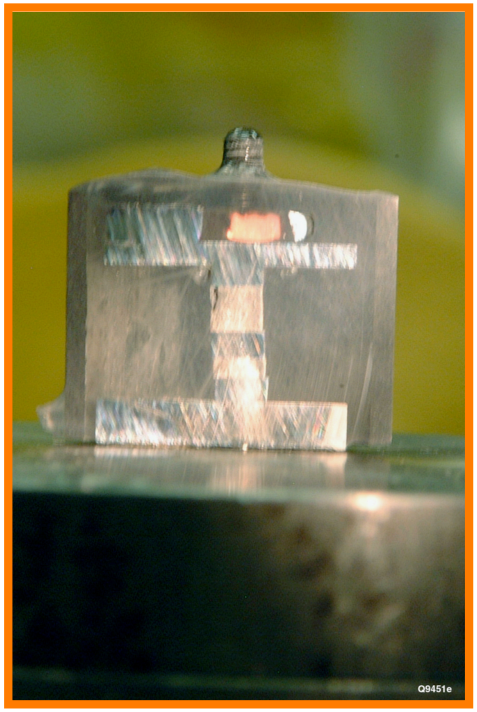
Fabrication Technology



- Remote injection casting of recycle fuel demonstrated at INL (ANL-W) in 1960's
- Tests samples are fabricated using arc-casting technique - not scalable
- Traditional injection-casting method needs modification for AFCI fuels
  - Am retention
  - Charge utilization
  - Waste minimization
- Two-step Approach to Advanced Casting Furnace Design
  - Bench-scale Casting System (BCS)
  - Engineering-scale Casting System (ECS)
- Casting simulation (Los Alamos National Laboratory)

Characterization Development

- Elemental, isotopic, and impurity analyses
- Microstructure (SEM, TEM)
- Phase Analysis (XRD, VT-XRD)
- Thermo-physical properties
  - Density
  - Thermal expansion (dilatometry)
  - Heat capacity (DSC)
  - Thermal diffusivity (LFA)
  - Thermal conductivity
- Thermal behavior
  - Phase transitions and heats of transition (DTA)
  - Annealing studies
- Mechanical properties
  - Micro indentation
- Fuel-cladding-chemical-interaction (FCCI)
  - Diffusion couples
- Advanced techniques under development (emphasis on irradiated samples)
  - STDM – thermal diffusivity at 50µm spatial resolution
  - LRUS – fundamental mechanical, elastic, and plastic data



ATR Metallic Fuel Irradiation Experiments

Metallic Fuel Alloy	Experiment	Irradiation Time (EFPDs)	Peak LHGR (W/cm)	Peak Fission Density (fiss/cm3)	Peak Burnup (% fissile)	Status
Pu-40Zr	AFC-1B	93	300	5.26E+20	5.7	
	AFC-1D	593	300	1.95E+21	33.3	
Pu-60Zr	AFC-1B	93	300	3.51E+20	7.0	
	AFC-1D	593	300	1.33E+21	39.6	
Pu-12Am-40Zr	AFC-1B	93	300	4.27E+20	5.9	
	AFC-1D	593	300	1.71E+21	34.1	
Pu-10Np-40Zr	AFC-1G	644	300	1.47E+21	17.6	
Pu-10Am-10Np-40Zr	AFC-1B	93	300	3.43E+20	5.5	
	AFC-1D	593	300	1.35E+21	30.8	*All in PIE*
U-25Pu-3Am-2Np-40Zr	AFC-1F	94	330	5.89E+20	6.7	
	AFC-1H	706	330	3.56E+21	38.0	
U-28Pu-7Am-30Zr	AFC-1F	94	330	6.38E+20	5.7	
	AFC-1H	706	330	3.97E+21	33.4	
U-29Pu-4Am-2Np-30Zr	AFC-1F	94	330	6.38E+20	5.9	
	AFC-1H	706	330	3.93E+21	36.2	
U-34Pu-4Am-2Np-20Zr	AFC-1F	94	330	5.35E+20	4.5	
	AFC-1H	706	330	3.48E+21	28.3	
U-20Pu-3Am-2Np-15Zr	AFC-2A	219	350	1.33E+21	6.7	
	AFC-2B	219	350	1.35E+21	7.0	
U-20Pu-3Am-2Np-1.0Ln*-15Zr	AFC-2A	219	350	1.42E+21	9.4	
	AFC-2B	219	350	1.44E+21	9.5	
U-20Pu-3Am-2Np-1.5Ln*-15Zr	AFC-2A	219	350	1.30E+21	10.7	*• AFC-2A in PIE • AFC-2B discharged And waiting results Of initial PIE on 2A*
	AFC-2B	219	350	1.31E+21	10.8	
U-30Pu-5Am-3Np-20Zr	AFC-2A	219	350	1.19E+21	8.0	
	AFC-2B	219	350	1.23E+21	8.2	
U-30Pu-5Am-3Np-1.0Ln*-20Zr	AFC-2A	219	350	1.30E+21	9.9	
	AFC-2B	219	350	1.32E+21	10.2	
U-30Pu-5Am-3Np-1.5Ln*-20Zr	AFC-2A	219	350	1.40E+21	11.0	
	AFC-2B	219	350	1.48E+21	11.3	

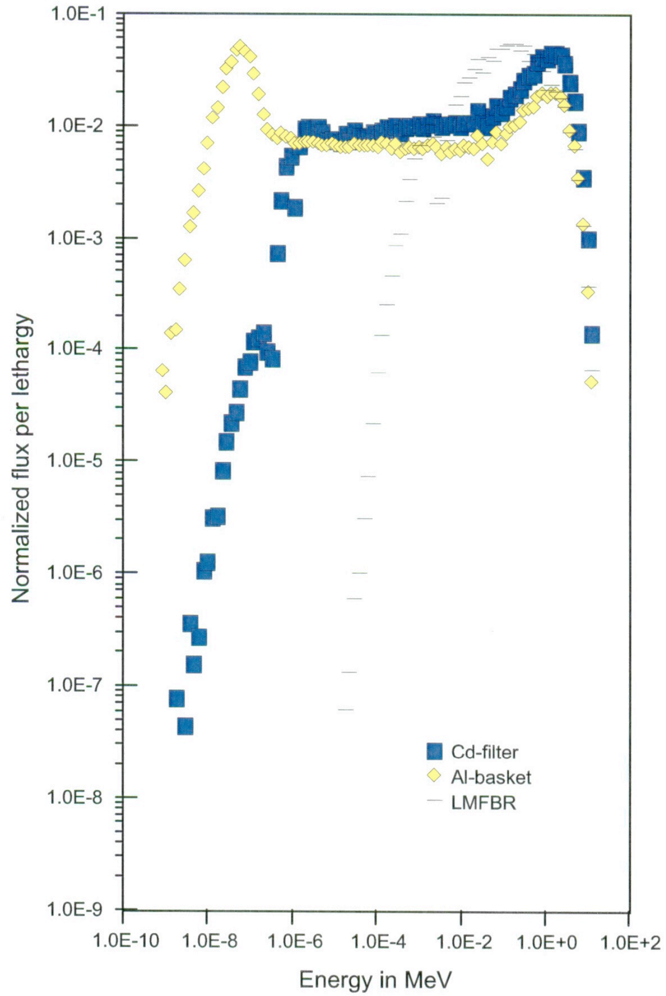
*Ln=6% La, 16% Pr, 25% Ce, 53% Nd

†Reported results through end of Cycle 142B

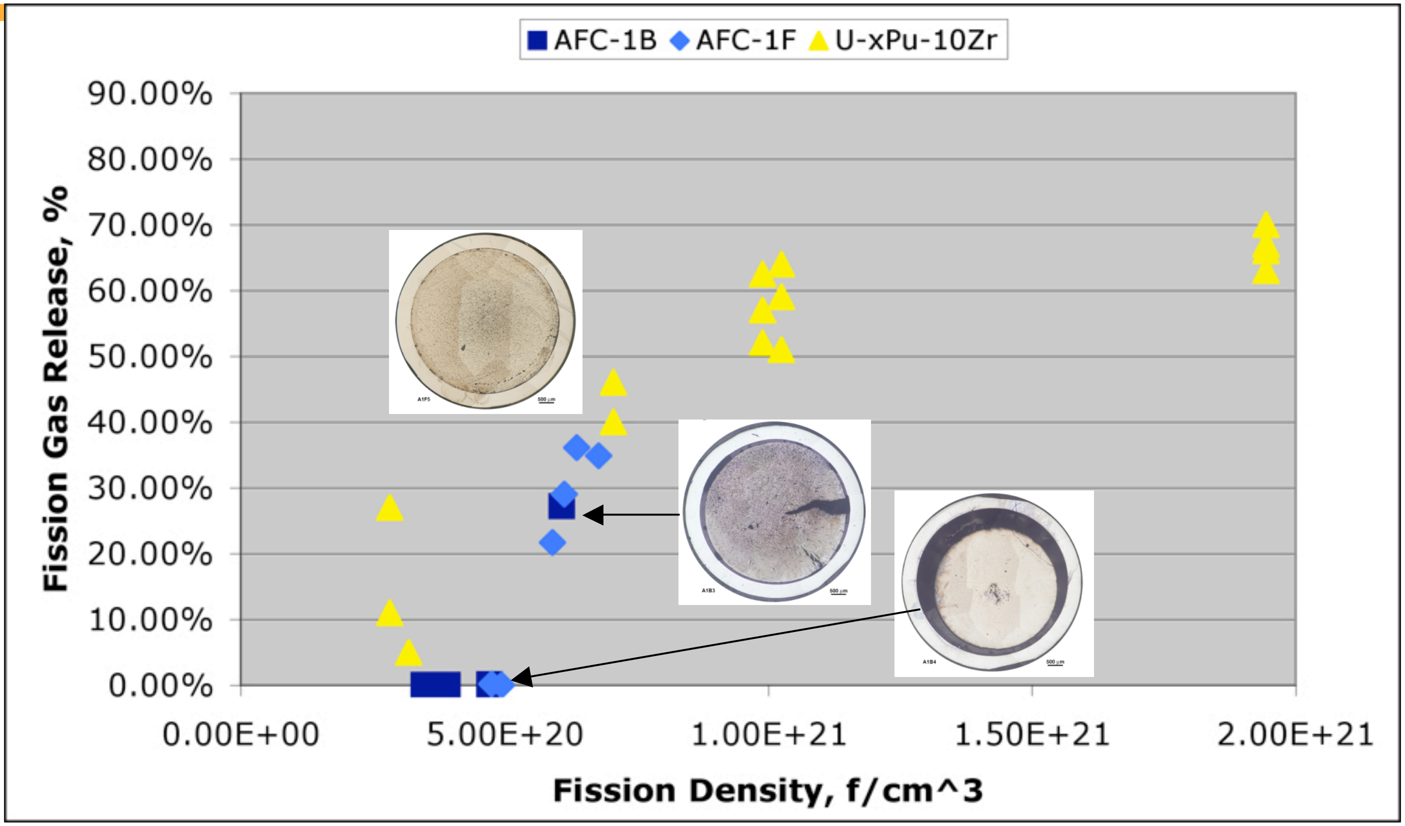
In addition oxide fuel tests continue: $(U_{0.80}Pu_{0.20}Np_{0.02}Am_{0.03})O_{1.98}$ and $(U_{0.80}Pu_{0.20}Np_{0.02}Am_{0.03})O_{1.95}$

Validation of ATR Tests with Fast Reactor Tests

- **FUTURIX-FTA completed**
  - Pu-12Am-40Zr and U-29Pu-4Am-2Np-30Zr
  - 240 EFPD, 10-12 at%
- **Next ATR test: AFC-2E**
  - Compositions
    - U-20Pu-10Zr (EBR II legacy fuel, injection cast slugs)
    - U-20Pu-10Zr (arc cast slugs)
    - U-Pu-3Am-2Np-10Zr (arc cast, same as fuel tested in EBR-II at the end of IFR)
  - Burnup: 10% and 20%



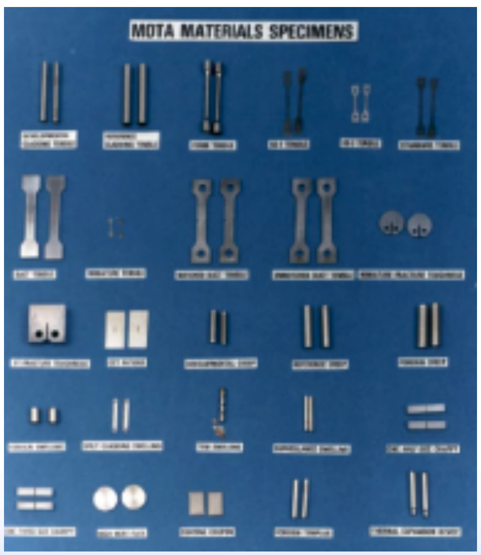
PIE Results to Date



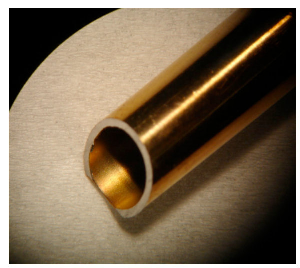
- Historical data from EBR-II fission gas release from U-Pu-Zr fuels shows incubation period followed by onset of swelling and gas release at ~70%.
- Onset of fission gas release from AFCI fuels also shows incubation period, perhaps somewhat longer than EBR-II fuel non-MA composition studies, but trending towards historical data behavior.
- Both low-fertile and non-fertile behave similarly
- Addition of minor actinides (Am, Np) effects minimal change in behavior.

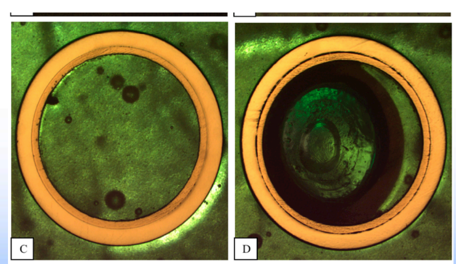
Cladding Development

- ACO-3 duct analysis
- Advanced Alloy Development
  - ODS steels analyses and welding studies
- Retrieval of FFTF/MOTA specimens
- NQA-1 Certified HT-9 Bar Stock Procurement and Tubing Fabrication
- Coating and Lining Tubes to Prevent FCCI

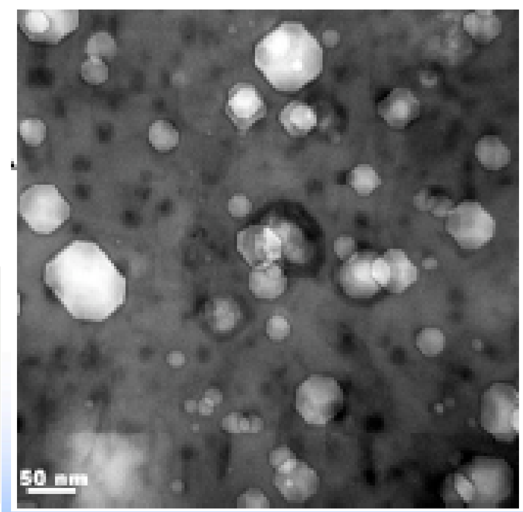


Typical specimens included in FFTF/MOTA irradiations.

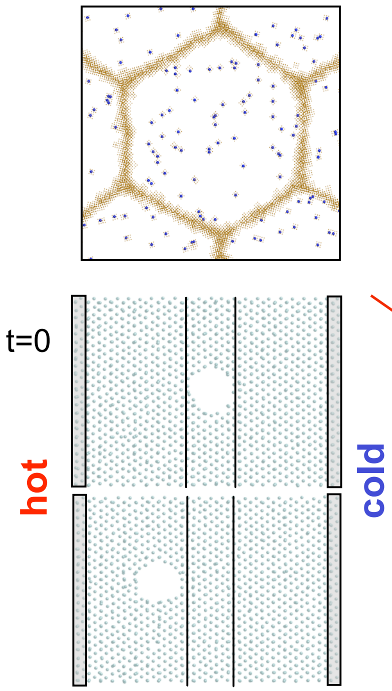


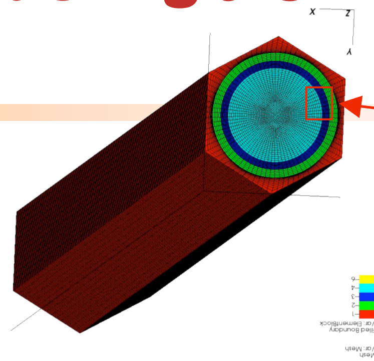


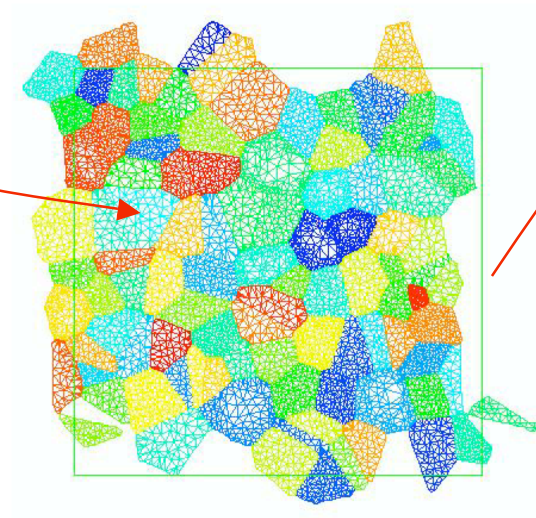
Initiation of void swelling observed in ACO-3 for Tirr=450C, Dose=155 dpa. Estimated swelling is 0.3%.

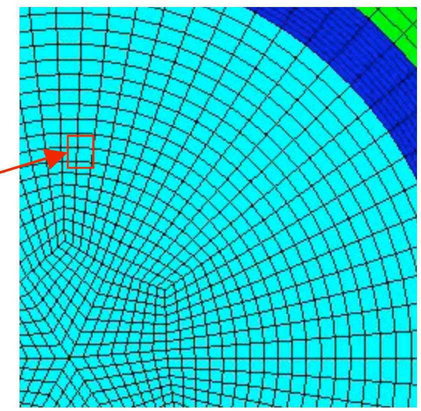


Fuel Performance Modeling & Simulation









Continuum level:
Continuum mechanics, PDEs, constitutive laws

'Mesoscale':
Effect of microstructural processes (fission-gas, voids, cracks, diffusion, …) on thermo-mechanical properties

Explicit incorporation of microstructural processes and atomic-level mechanisms is critical towards establishing a predictive, materials-physics based fuels-performance capability

Summary and Conclusions

- As part of the fuel cycle R&D, considerable efforts are invested into the development of advanced fuels for transmutation applications.
- The research to-date indicates that there are no show stoppers in using TRU-bearing metal fuels in fast reactors.
- Additional studies are needed for demonstrating large-scale applications.
- A goal-driven science-based R&D program will continue to investigate efficient applications of metal fuels in future fast reactors.
- The program also is pursuing other fuel forms containing transuranics
  - Oxides as part of baseline technology
  - CERCERs and CERMETs for enhanced performance